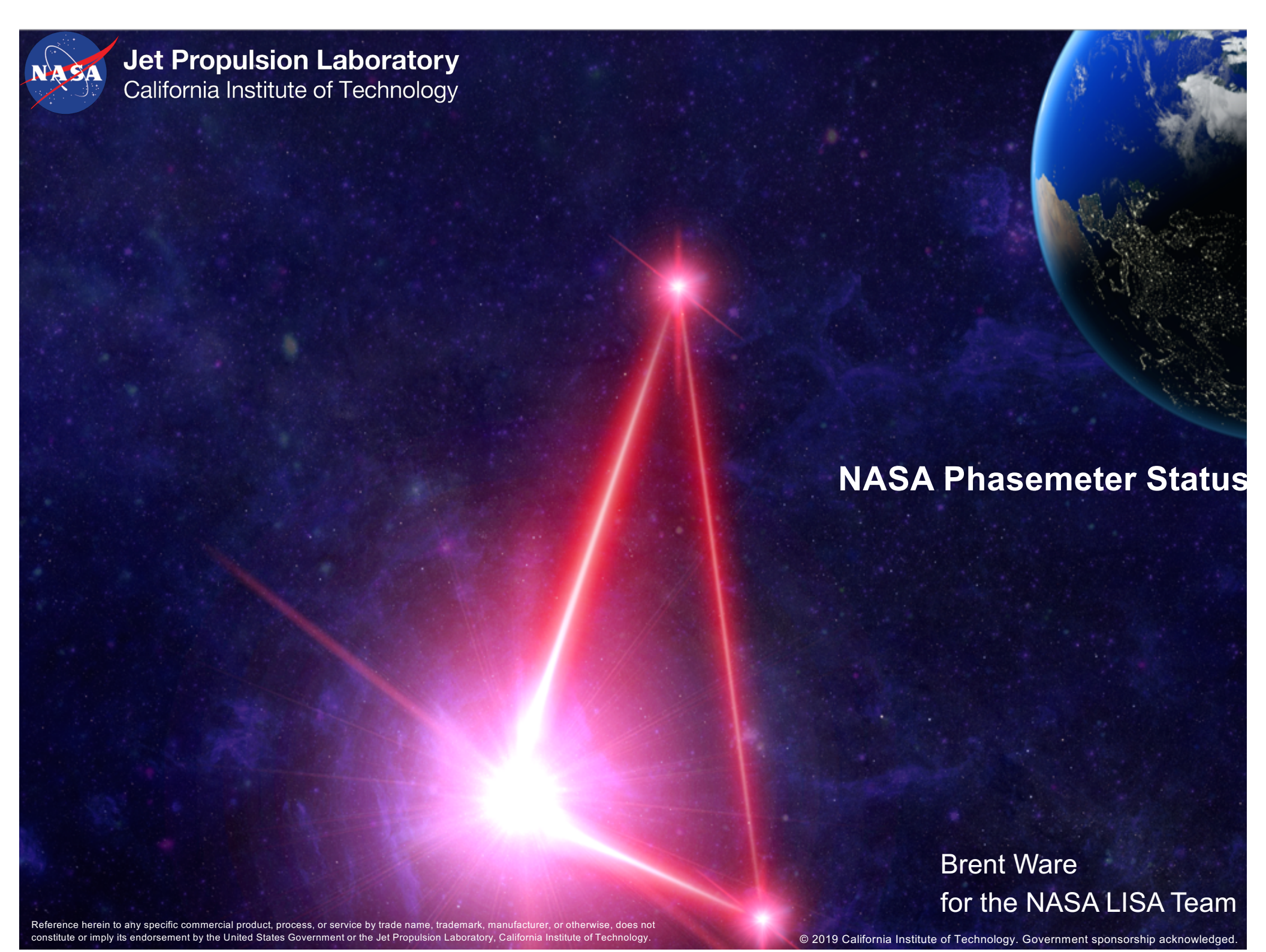
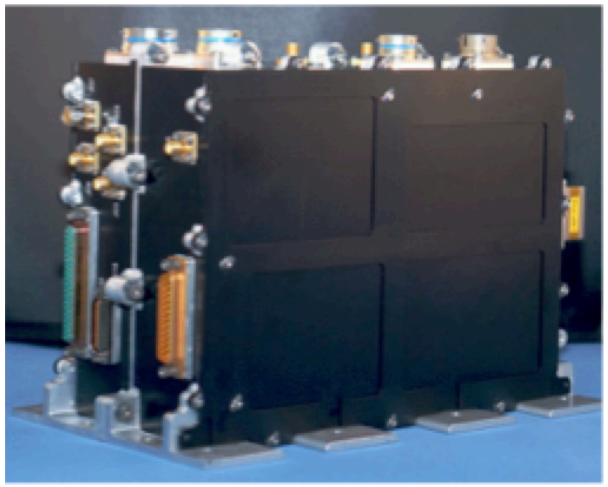


Phasemeter Technology Development Overview

- Role in Flight System
  - **Phasemeter produces science data**,
    Differential Wavefront Sensing (DWS),
    Laser frequency stability control,
    Produces diagnostic telemetry,
    Key part of link acquisition,
  - **Team part of Laser Stabilization effort**
- Development Team
  - PDM: W. Klipstein;
    K. McKenzie, Brent Ware, Jeff Dickson, Bob Spero, Brian Bachman, Chris Woodruff, Jehhal Liu, Sam Francis
- Development Highlights
  - Flight phasemeter demonstrated first inter-spacecraft laser interferometry in space June 2018 (GRACE-FO LRI)
  - **Design Cycle 1 (June 2018 and September 2020)**
    Produce a scalable version of the GRACE-FO instantiation of the LISA phasemeter working with with Trident Systems Inc. (up to 40 phasemeter inputs)
  - **Design Cycle 2, (Oct 2018 to Sept 2022)**
    targeting more advanced flight implementation,
    Reach Technology Readiness Level (TRL) 6 by 30 September 2022



LRI Flight Phasemeter

Time Delay Interferometry with the LISA Phasemeter

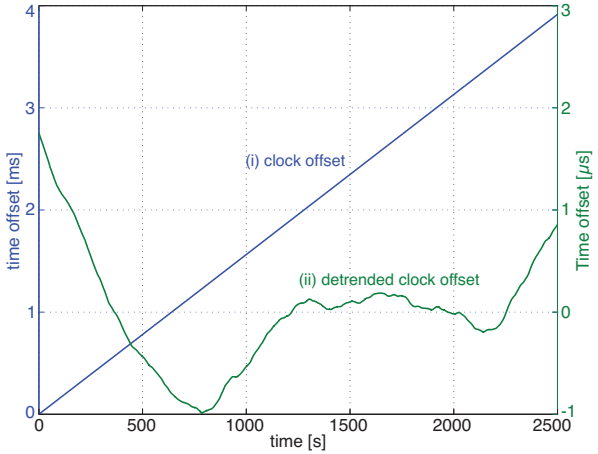
JPL LISA interferometer testbed built to demonstrate the phasemeter, TDI, and measurement system performance to TRL 4.

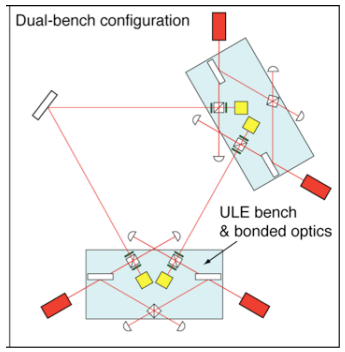
PRL 104, 211103 (2010) PHYSICAL REVIEW LETTERS week ending 28 MAY 2010

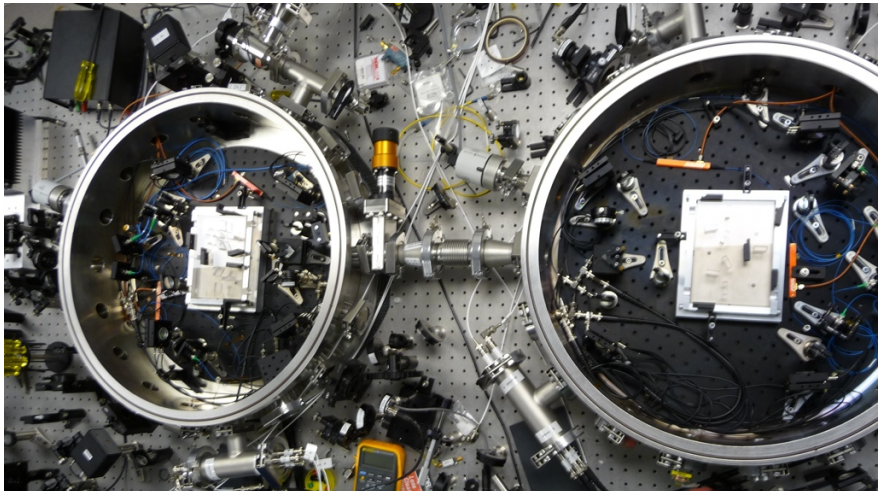
Experimental Demonstration of Time-Delay Interferometry for the Laser Interferometer Space Antenna

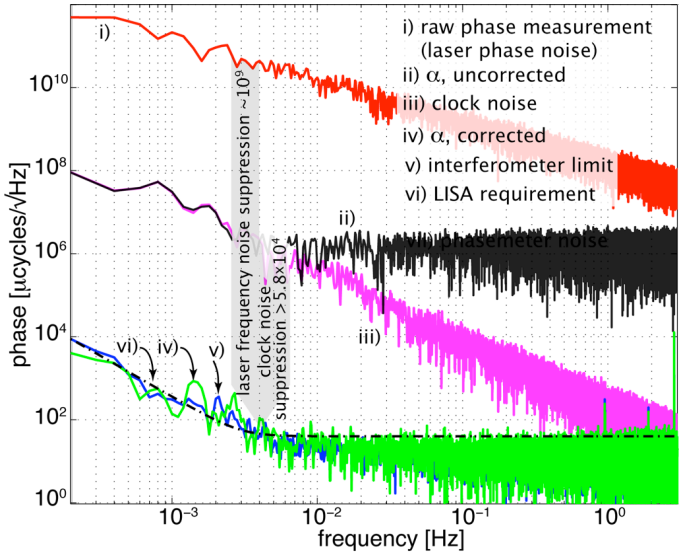
Glenn de Vine,* Brent Ware, Kirk McKenzie, Robert E. Spero, William M. Klipstein, and Daniel A. Shaddock†
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA
(Received 1 April 2010; published 27 May 2010)

- Frequency noise removal to interferometer displacement limit
- Clock tone transfer via GHz phase modulation
- Stationary arms but changing clock offset >1us/s
- Interpolation of data streams onto common time-base
- Ranging to 20 cm
- PRN data comms between spacecraft (20kbps)









Trident Phasemeter Progress: Overview

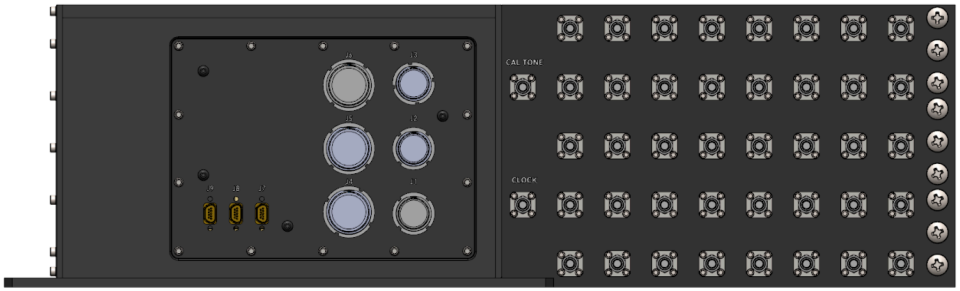
- Trident's Laser Interferometer Space Antenna Multi-Function RF Electronics Unit (LISA-MFREU) is a 7-slot 3U VPX formfactor multi-channel receiver system. The system is composed of:
  - Up to 5 card x 8 phasemeter inputs per card = 40 channels
    - *3 cards x 8 channels is the contracted delivery*
  - JPL phasemeter firmware to be incorporated after delivery

- Manufacturing readiness review complete
  - Backplane card sent for fabrication
  - Mezzanine (analog, ADC) and FPGA cards sent for fabrication
- Functional requirements document updated;
- JPL determining details of phasemeter firmware interface
  - Firmware architecture for LISA phasemeter "base block" in progress.
  - FPGA firmware of trident box is flexible for early testing; may need to streamline

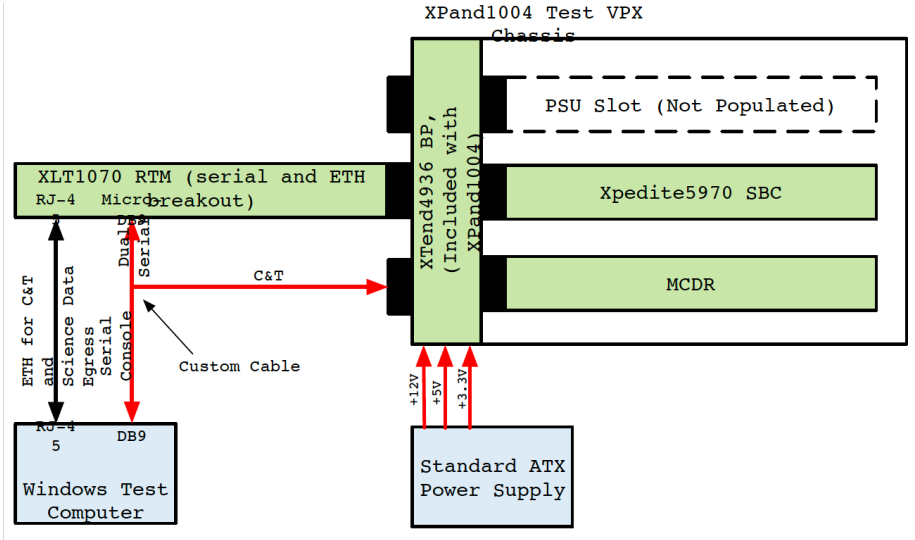
Trident Phasemeter progress: GSE and testing

- Test plan documents in place; JPL review complete and comments delivered
  - I&T readiness review (May 2nd) with GSFC
- GSE required to test card without chassis on order
  - GSE on track
- Readying GSE software with Trident data format
  - Trident has delivered data format code; JPL can design/test software tools around this

Rack mount system; 40 channels



Intermediate GSE for card testing before



Preparations for Trident Visit - May 2nd

- Attendees : Sridhar Manthripragada, Ira Thorpe, Norman Rioux, Brent Ware, Chris Woodruff, Kirk McKenzie,
- Tentative agenda: 9am Start
  - Meet and Greet
  - Trident/JPL Program overview
  - Look at representative hardware
  - I&T Readiness Review
  - ….

- Location Trident Systems Inc.

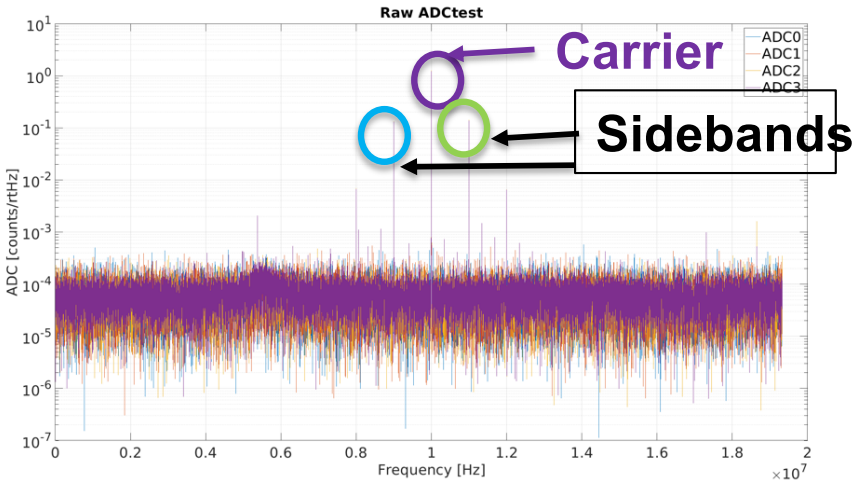
10201 Fairfax Blvd # 300, Fairfax, VA 22030

Phasemeter ASIC Progress Update

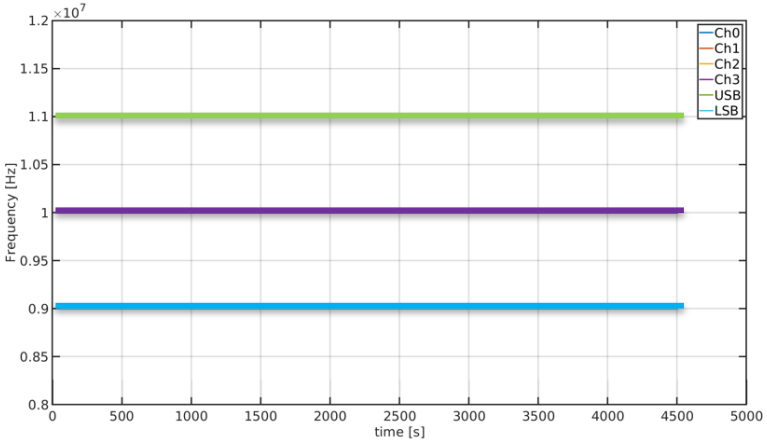
- Full ASIC CAD tool set acquired and installed at JPL
- NDAs in progress to access **P**rocess **D**esign **K**it with ON Semiconductor, TSMC, and GlobalFoundries
- Initial phasemeter design synthesized with Cadence demonstration PDK
  - Cadence verification tool check successful
- Design of chip register set and external interface in progress
- First phasemeter chip expected early 2020

Multitone tracking on the GRACE FO LRI phasemeter: First step – Functional Demo

- The LRI phasemeter flight software and FPGA code were modified to track the sideband frequencies and output the data in the science phase data packet.
- Test completed on LRI Phasemeter prototype
- Next step is to implement carrier-assisted tracking in the FPGA – needed for low SNR signals



Results show functional demo success

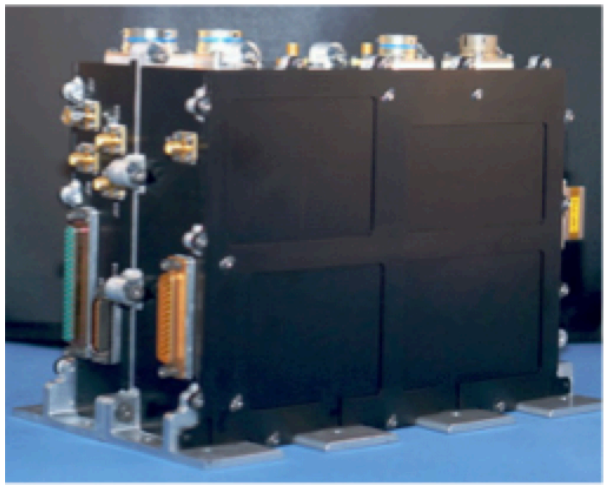


LRI Flight Phasemeter aka Laser Ranging Processor (LRP)

The LRP implements the LISA phase tracking and frequency control algorithms, including:

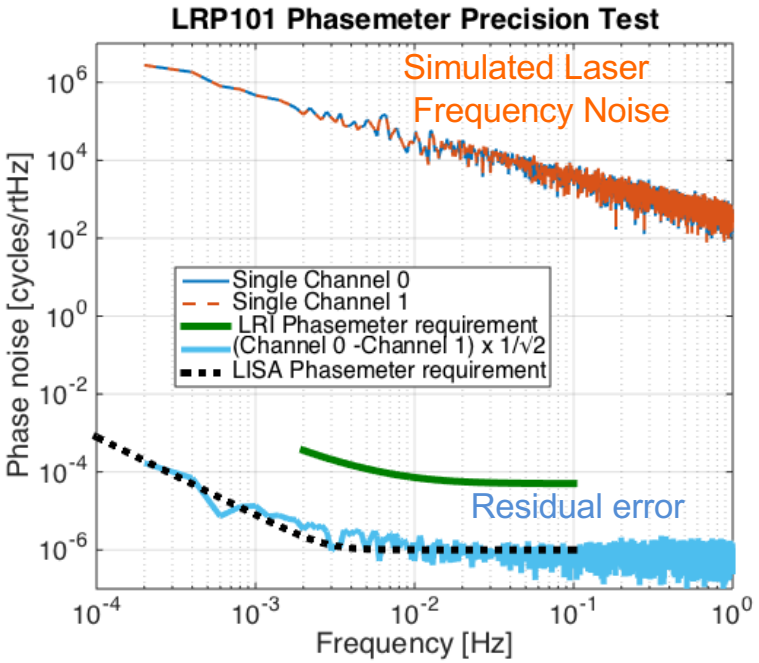
- Phase tracking
- Differential wavefront sensing (and control)
- Laser Phase Locking
- Laser frequency stabilization

- Has only 4 input channels (vs ~34 for LISA)
- Relaxed precision requirement, but ~ LISA performance



LRI Flight model Phasemeter

- Same LFN
- Same optical power
- Same signal processing chain
- Same phaselocking
- Same PDH cavity locking
- Similar acquisition strategies



Plans

- Development Highlights
  - Flight phasemeter demonstrated first inter-spacecraft laser interferometry in space June 2018 (GRACE-FO LRI)
  - **Design Cycle 1 (June 2018 and September 2020)**
    - Produce a scalable version of the GRACE-FO instantiation of the LISA phasemeter working with Trident Systems Inc. (up to 40 phasemeter inputs)
  - Design Cycle 2, (Oct 2018 to Sept 2022) targeting more advanced flight implementation,
    - Reach Technology Readiness Level (TRL) 6 by Q3 2022

- NASA/Ball has developed a flight cavity and frequency stabilization electronics and algorithms applicable to LISA
  - Incorporate lessons learned into slightly modified design for LISA

Summary

- Theory, simulations, and testbeds by, or funded by, NASA have retired significant LISA TDI, phase measurement, and frequency control risks

- The GRACE Follow-on LRI mission parameters have many similarities to LISA
  - The LRI is a successful and relevant technology demonstrator for LISA
  - Increases maturity of key LISA technologies (for US: advanced phasemeter and Optical Cavity)
  - US/German partnership

- NASA is maturing a LISA flight phasemeter building on the GRACE Follow-on flight phasemeter heritage
  - Design cycle 1 (Trident 40 channel phasemeter chassis) on schedule for delivery 1 December 2019, performance testing July 2019.
  - Design cycle 2 (ASIC) on schedule for early 2020